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**Liu et al.**

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(54) **REFRACTIVE INDEX SENSOR FOR ANALYZING AN ANALYTE, AND METHOD OF FABRICATING THEREOF**

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CPC ..... **G01N 21/41** (2013.01); **G01N 21/55** (2013.01); **G02B 6/10** (2013.01)

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USPC ..... 356/128–137; 385/2, 12, 10, 37, 39, 385/129, 146

See application file for complete search history.

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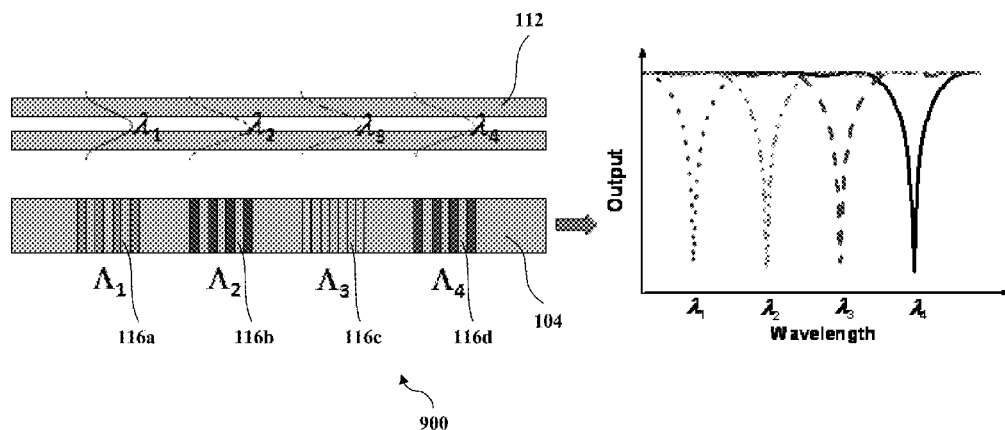
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(57) **ABSTRACT**

A refractive index sensor is provided for analyzing an analyte, the sensor including: a strip waveguide for receiving an input light signal therein and transmitting the light signal, subject to manipulation as it propagates through the strip waveguide, to a detector for analysis with respect to the analyte; and a slot waveguide for sensing the analyte disposed thereon and for receiving a sensing signal, corresponding to said manipulation of the light signal, from the strip waveguide, wherein a grating is formed on a surface of the strip waveguide to enable coupling of the sensing signal from the strip waveguide to the slot waveguide, and the sensor is configured with enhanced sensitivity based on a sensitivity difference between the slot waveguide and the strip waveguide, and/or a group index difference between the slot waveguide and the strip waveguide.

**20 Claims, 11 Drawing Sheets**



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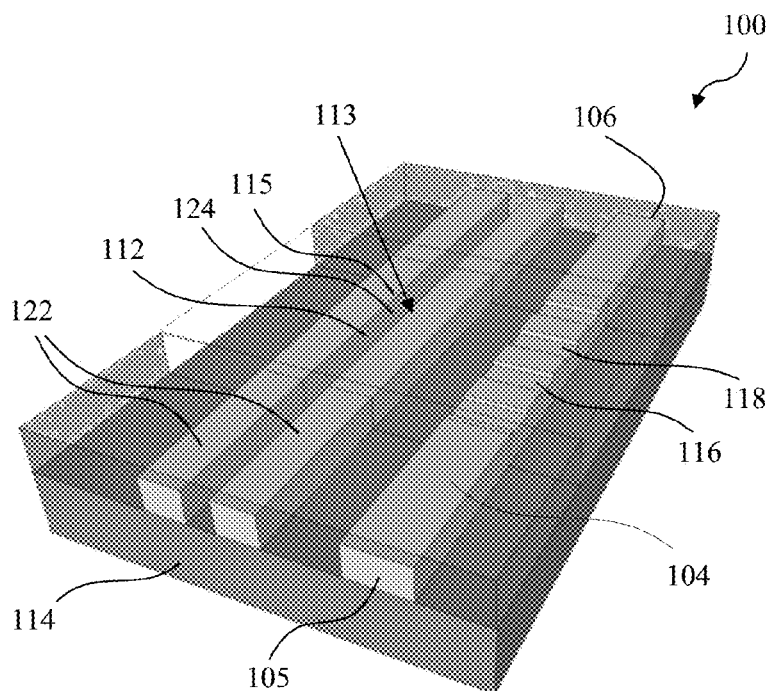


FIG. 1A

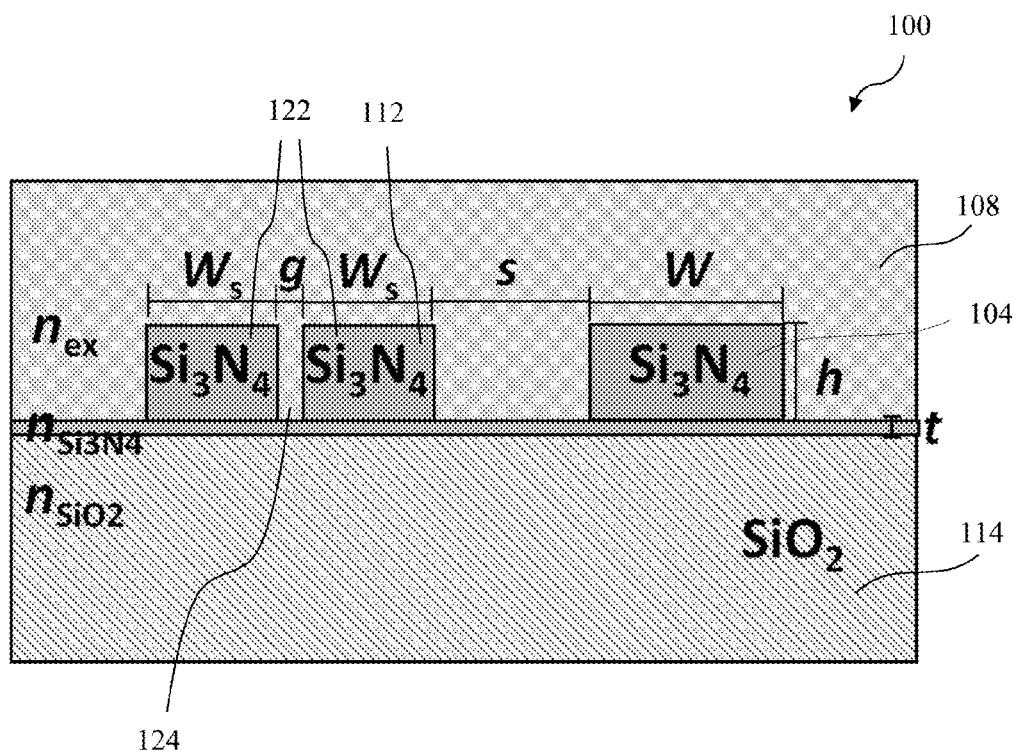


FIG. 1B

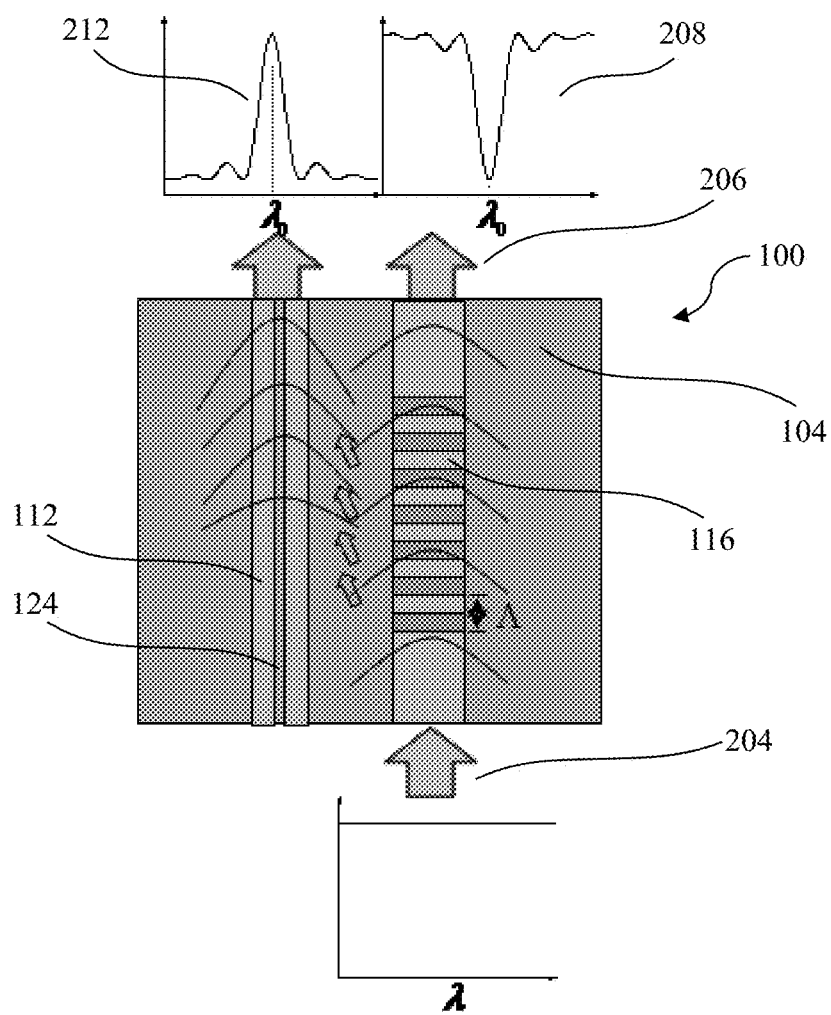


FIG. 2

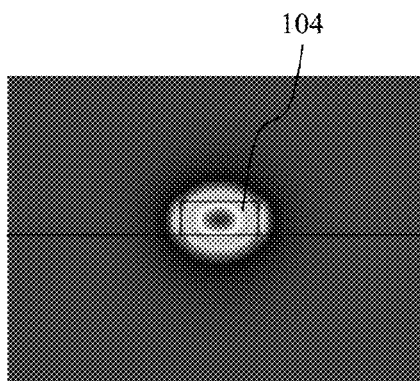


FIG. 3A

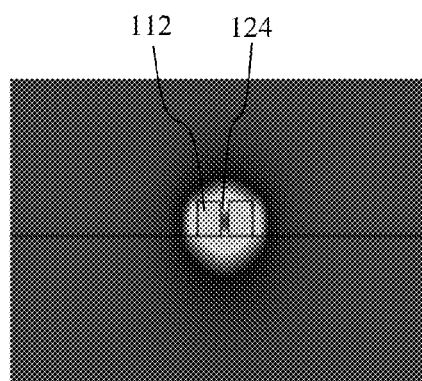


FIG. 3B

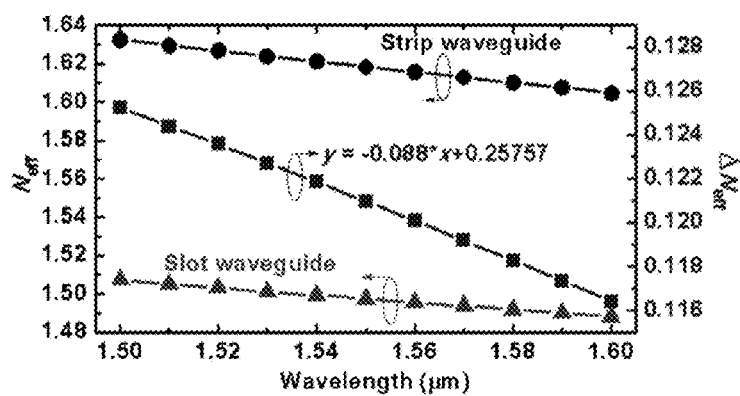


FIG. 3C

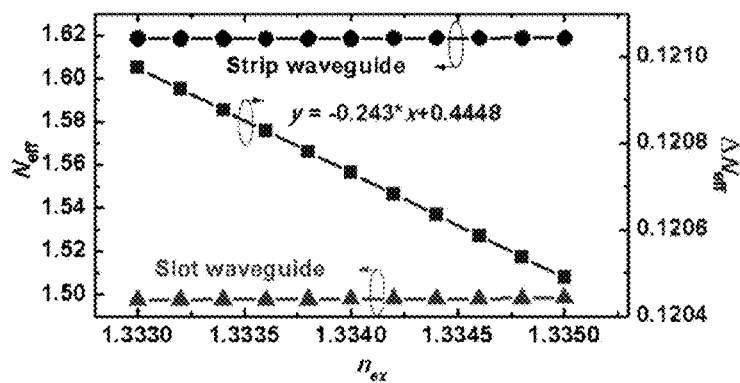


FIG. 3D

FIG. 4

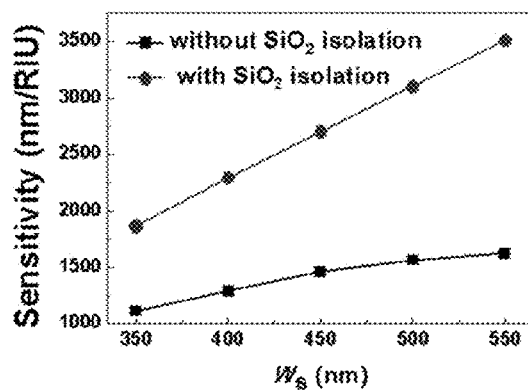


FIG. 5A

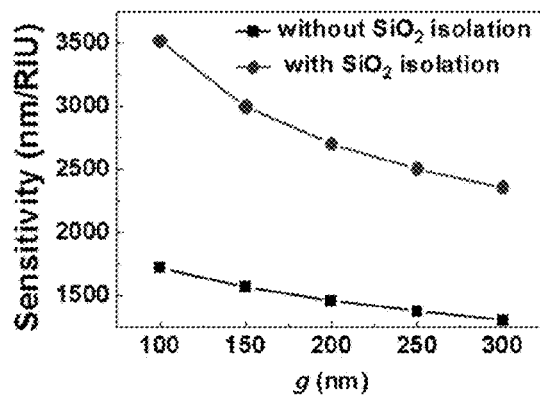


FIG. 5B

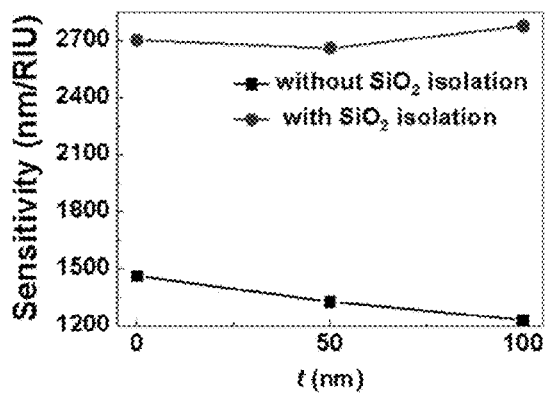


FIG. 5C

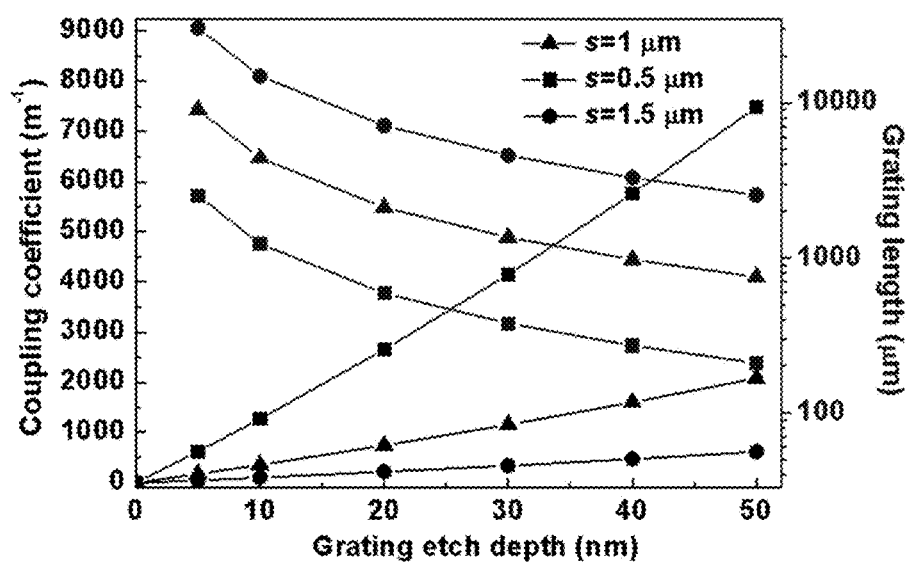
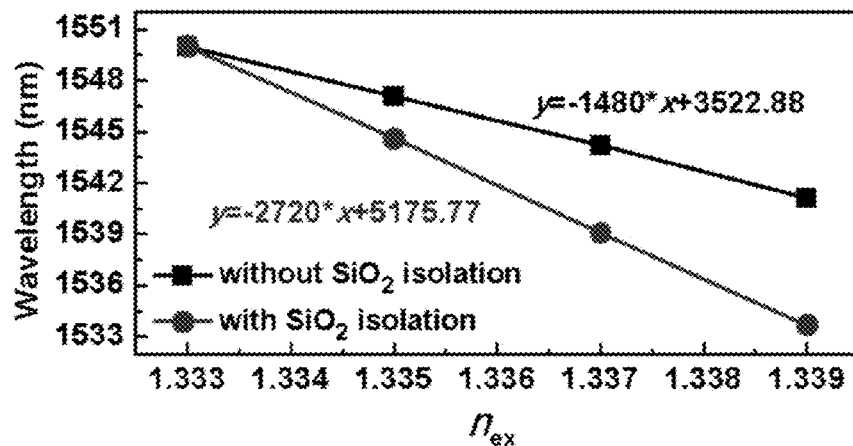
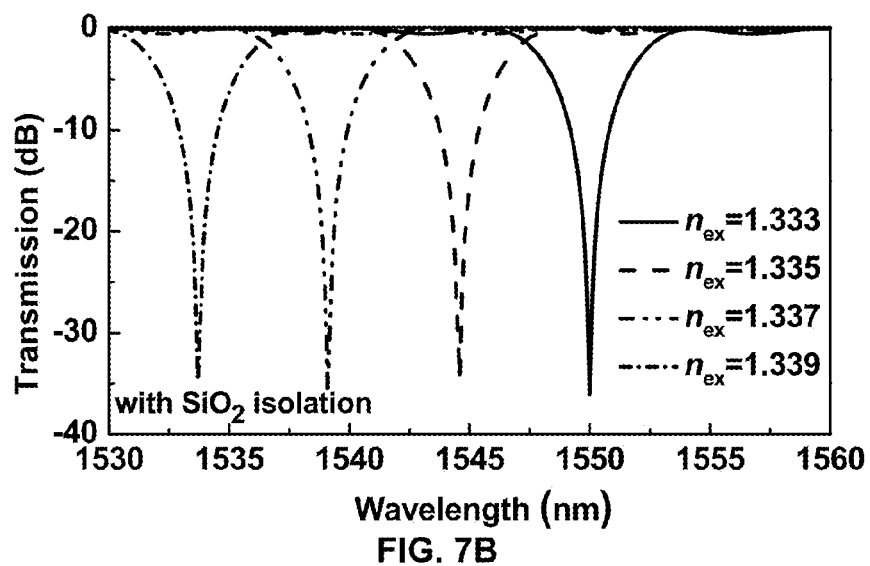
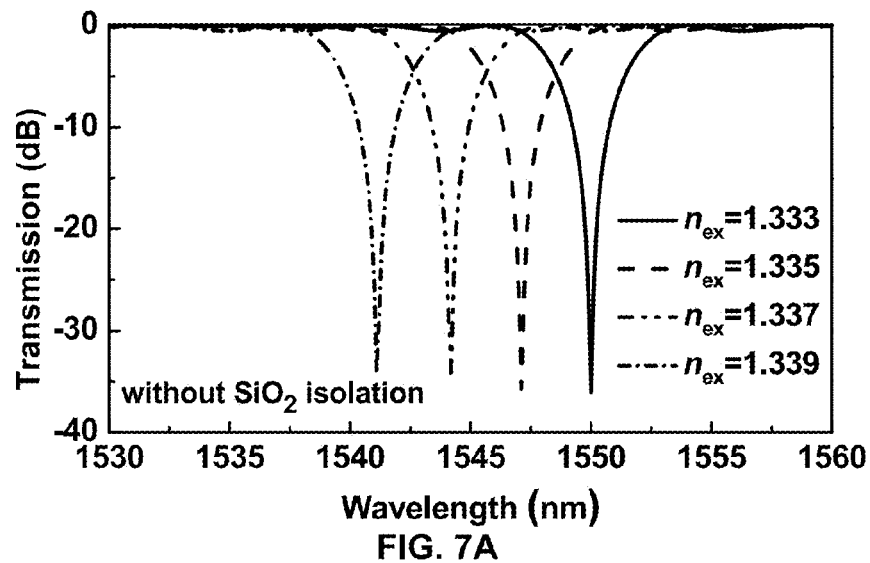


FIG. 6





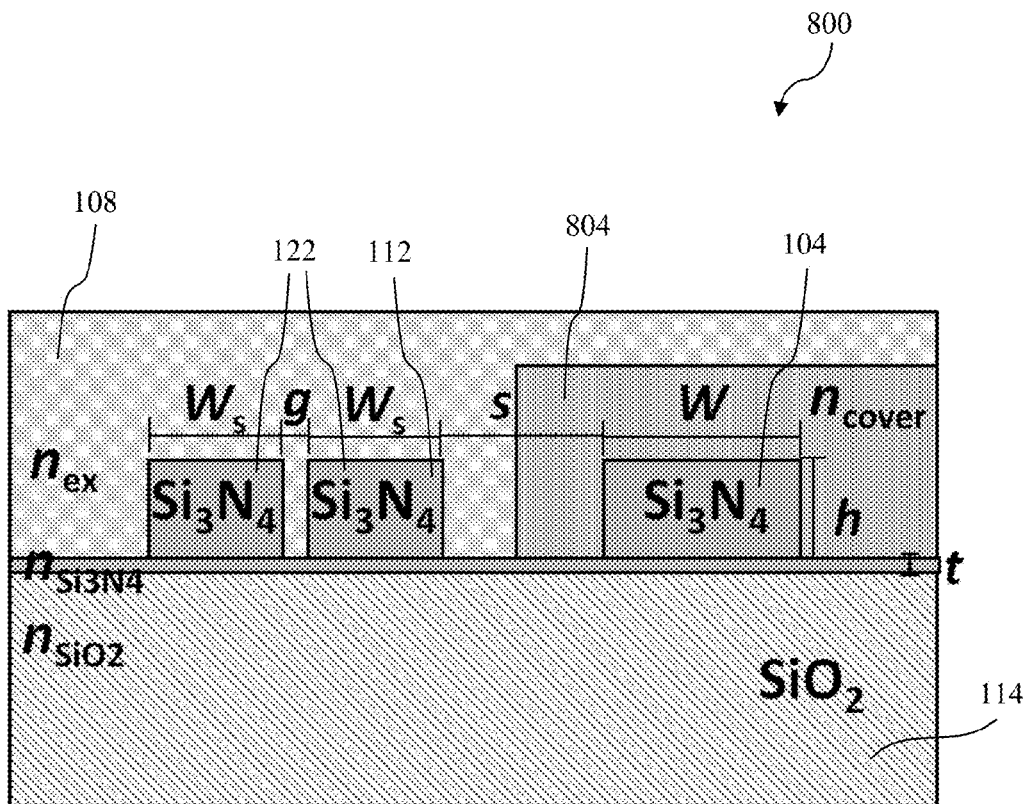


FIG. 8A

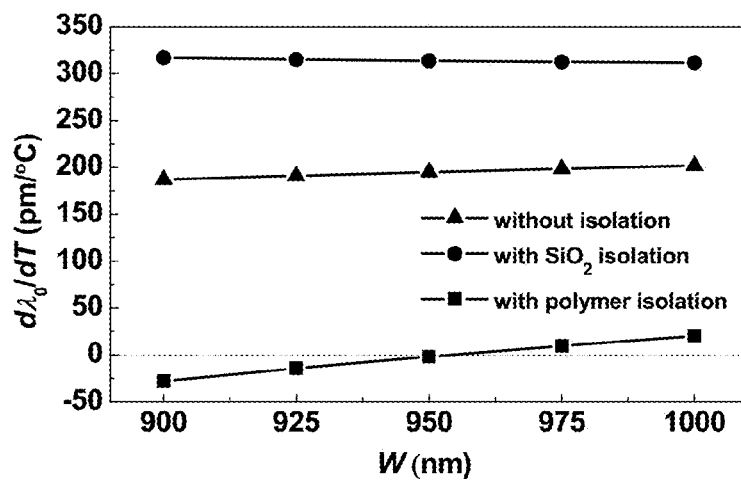


FIG. 8B

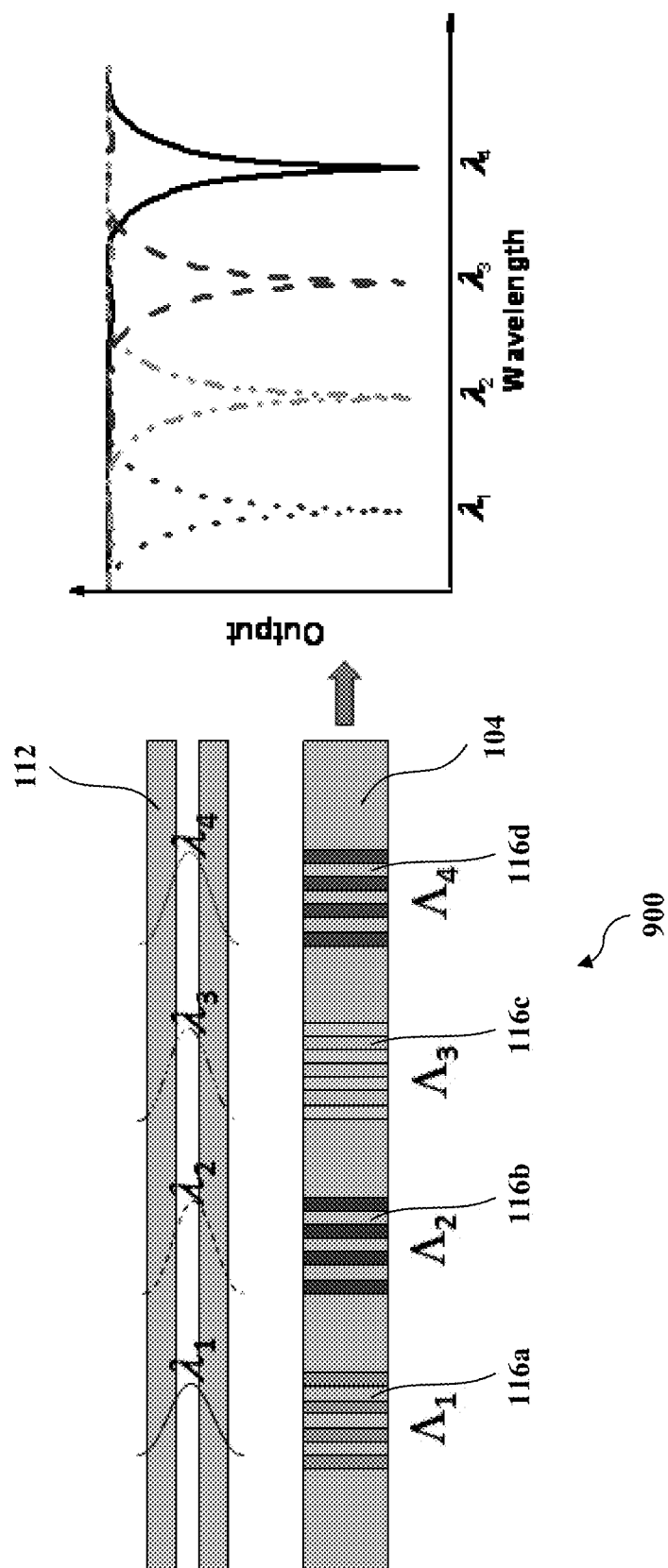


FIG. 9

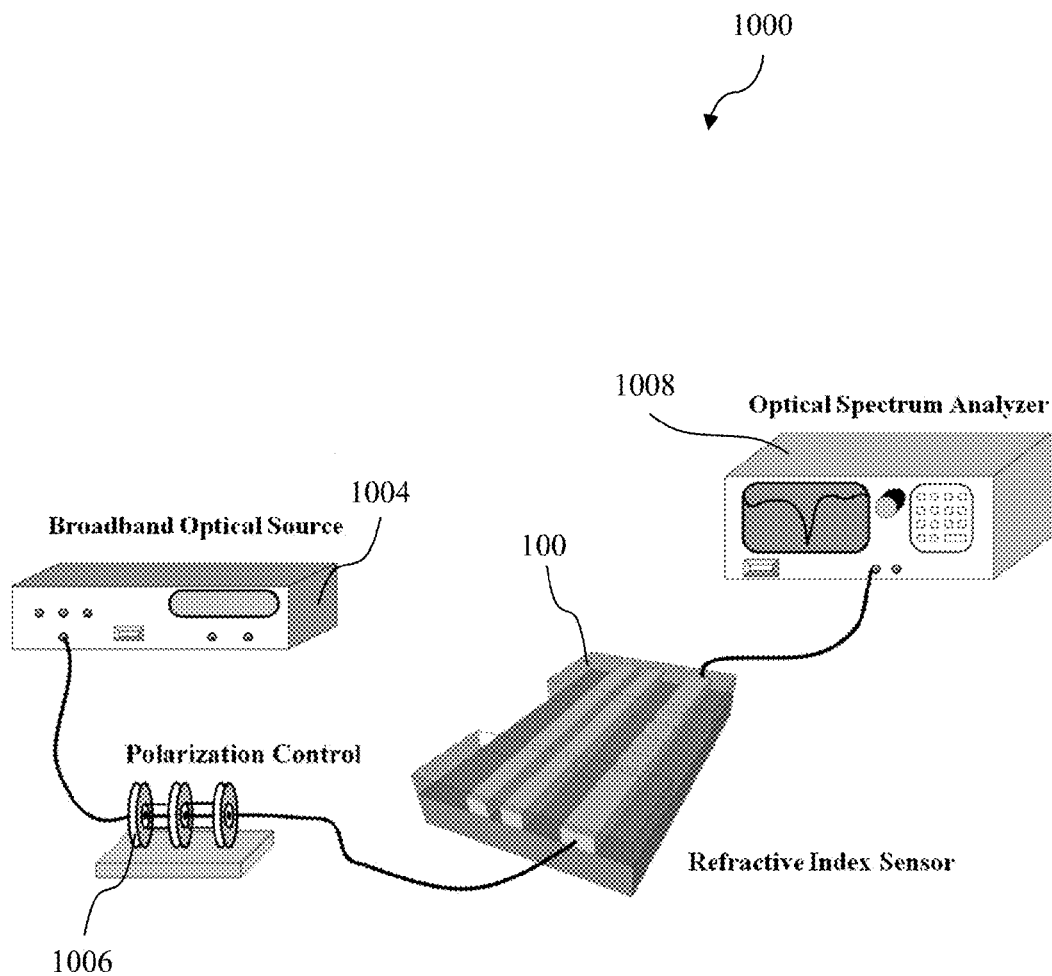


FIG. 10

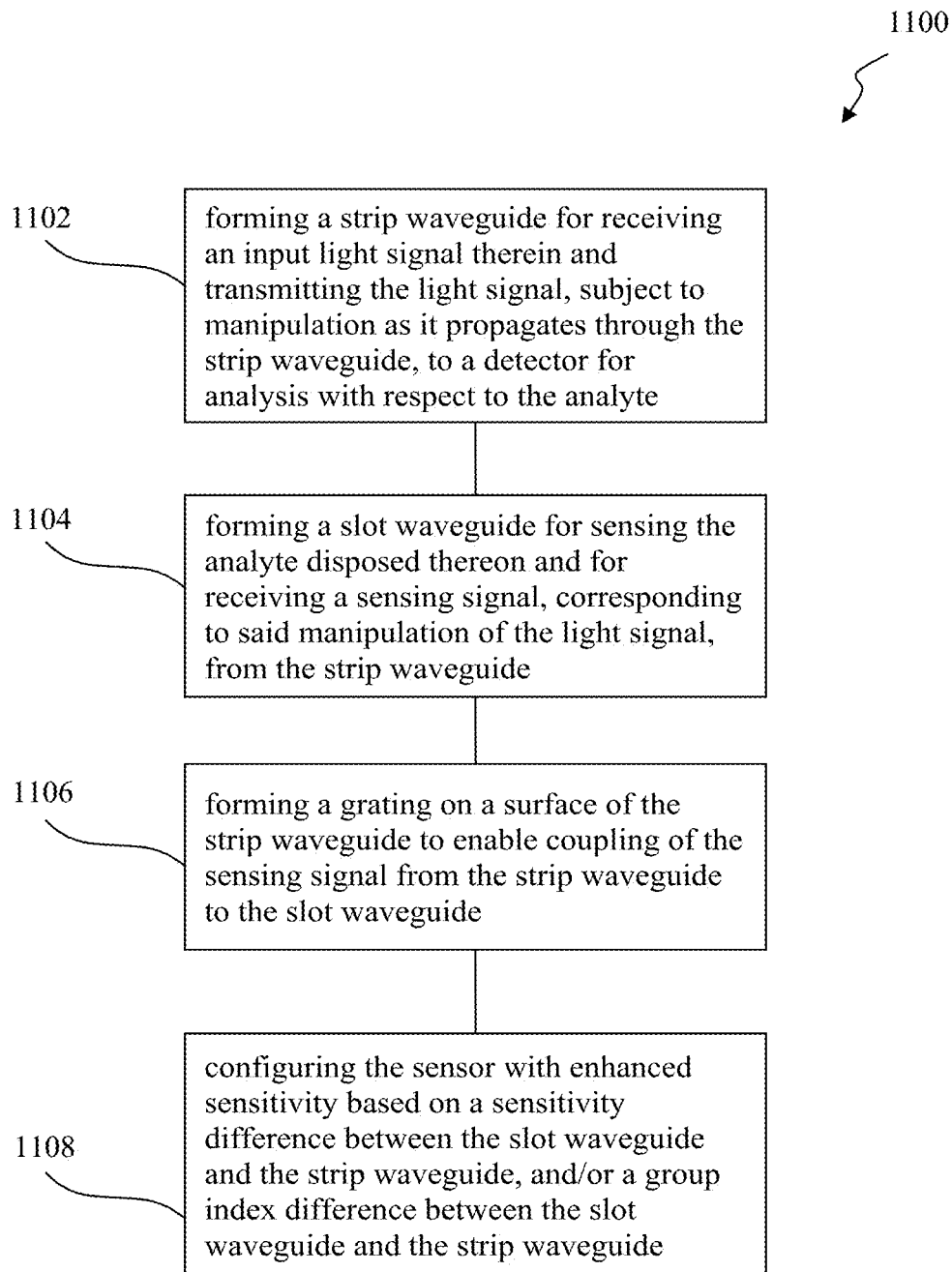


FIG. 11

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# REFRACTIVE INDEX SENSOR FOR ANALYZING AN ANALYTE, AND METHOD OF FABRICATING THEREOF

## CROSS-REFERENCE TO RELATED APPLICATION

The present application is the U.S. National Stage under 35 U.S.C. §371 of International Patent Application No. PCT/SG2013/000432, filed 8 Oct. 2013, which claims priority to Singapore Application No. SG 201207483-7, filed 8 Oct. 2012, the disclosures of which are hereby incorporated herein by reference.

## FIELD OF INVENTION

The present invention generally relates to a refractive index sensor for analyzing an analyte, such as in biochemical analysis, a method of fabricating the refractive index sensor, and more particularly, to a highly sensitive refractive index sensor.

## BACKGROUND

Optical refractive index (RI) sensors have been extensively investigated for a number of applications and play a prominent role in biochemical analysis. Among the existing biochemical RI sensors, those based on integrated optical waveguides are of interest because of their high sensitivity, small size, and high scale integration. Recently, RI sensors based on certain types of slot waveguides have attracted interest due to their ability to provide high optical intensity in a subwavelength-scale low refractive index region (slot region). With such slot waveguides, larger light-analyte interaction in the slot region, and hence higher sensitivity, can be obtained as compared to conventional strip waveguides. Up to now, slot waveguide sensors based on ring resonator, Mach-Zehnder interferometer, Bragg grating, and directional coupler have been reported. The reported slot waveguide ring resonator sensors may exhibit sensitivity of about two times larger (about 212 nm/RIU (refractive index unit)) than that of ring resonator sensors based on conventional strip waveguides.

However, it would be beneficial to further enhance the sensitivity of the RI sensor to improve its analyte detection-measurement abilities in order to detect measure biomolecules with very low detection threshold for example. In addition, because of the complex nature of most biological interactions, it would also be beneficial to provide an RI sensor capable of wavelength multiplexed measurements.

A need therefore exists to provide a reflective index (RI) sensor for analyzing an analyte which is highly sensitive, and preferably also capable of wavelength multiplexed measurements. It is against this background that the present invention has been developed.

## SUMMARY

The present invention seeks to overcome, or at least ameliorate, one or more of the deficiencies of the prior art mentioned above, or to provide the consumer with a useful or commercial choice.

According to a first aspect of the present invention, there is provided a refractive index sensor for analysing an analyte, the sensor comprising:

a strip waveguide for receiving an input light signal therein and transmitting the light signal, subject to manipulation

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as it propagates through the strip waveguide, to a detector for analysis with respect to the analyte; and a slot waveguide for sensing the analyte disposed thereon and for receiving a sensing signal, corresponding to said manipulation of the light signal, from the strip waveguide,

wherein a grating is formed on a surface of the strip waveguide to enable coupling of the sensing signal from the strip waveguide to the slot waveguide, and the sensor is configured with enhanced sensitivity based on a sensitivity difference between the slot waveguide and the strip waveguide, and/or a group index difference between the slot waveguide and the strip waveguide.

Preferably, the sensor further comprises a substrate, wherein the strip waveguide and the slot waveguide are disposed on the substrate so as to be spaced apart and substantially parallel to each other.

Preferably, the sensing signal is in the form of a light signal, and the grating has a grating period configured to couple light signal at a particular resonant wavelength from the strip waveguide to the slot waveguide.

Preferably, the slot waveguide has a mode index which is subject to change based on the analyte disposed thereon, the change in the mode index results in a shift in the particular resonant wavelength of the light signal coupled from the strip waveguide to the slot waveguide, thereby enabling analysis of the analyte based on the shift in the particular resonant wavelength.

Preferably, the sensor is configured such that its sensitivity (S) is determined based on the following equation:

$$S = \lambda_0 \frac{\Delta S}{\Delta N_g}$$

where,  $\lambda_0$  is the particular resonant wavelength of the light signal,  $\Delta S$  is the sensitivity difference between the slot waveguide and the strip waveguide, and  $\Delta N_g$  is the group index difference between the slot waveguide and the strip waveguide.

Preferably, the sensor is configured such that the sensitivity difference between the slot waveguide and the strip waveguide is increased and/or the group index difference between the slot waveguide and the strip waveguide is reduced.

Preferably, the strip waveguide is isolated to decrease its sensitivity so as to increase the sensitivity difference between the slot waveguide and the strip waveguide.

Preferably, the strip waveguide is enclosed by an isolation layer made of SiO<sub>2</sub> to isolate the strip waveguide from the analyte.

In another embodiment, the strip waveguide is enclosed by an isolation layer made of a polymer material to isolate the strip waveguide from the analyte.

Preferably, the polymer material has a thermal-optic coefficient selected for compensating a positive or negative temperature dependence of the sensor so as to reduce the temperature dependence of the sensor.

Preferably, the polymer material is made of WIR30-490 or SU-8.

Preferably, a width of the strip waveguide is configured to be about 600 nm to about 1000 nm.

Preferably, one or more parameters of the slot waveguide are configured to increase its sensitivity so as to increase the sensitivity difference between the slot waveguide and the

strip waveguide, said one or more parameters include a width of the slot waveguide and/or a width of a gap of the slot waveguide.

Preferably, the slot waveguide is configured such that the width of the slot waveguide is increased and/or the width of the gap is reduced.

Preferably, the width of the slot waveguide is in the range of about 350 nm to about 550 nm, and the width of the gap is in the range of about 50 nm to about 300 nm.

Preferably, a plurality of gratings, spaced apart from each other, is formed on the surface of the strip waveguide, each grating having a different grating period configured for coupling a sensing signal at a respective resonance wavelength to the slot waveguide, thereby enabling wavelength multiplexed measurement.

Preferably, the slot waveguide and/or the strip waveguide are made of silicon nitride ( $\text{Si}_3\text{N}_4$ ).

According to a second aspect of the present invention, there is provided a method of fabricating a refractive index sensor for analysing an analyte, the method comprising:

forming a strip waveguide for receiving an input light signal therein and transmitting the light signal, subject to manipulation as it propagates through the strip waveguide, to a detector for analysis with respect to the analyte; and

forming a slot waveguide for sensing the analyte disposed thereon and for receiving a sensing signal, corresponding to said manipulation of the light signal, from the strip waveguide,

wherein the method further comprises forming a grating on a surface of the strip waveguide to enable coupling of the sensing signal from the strip waveguide to the slot waveguide, and

configuring the sensor with enhanced sensitivity based on a sensitivity difference between the slot waveguide and the strip waveguide, and/or a group index difference between the slot waveguide and the strip waveguide.

According to a third aspect of the present invention, there is provided a refractive index sensor device for analysing an analyte, the sensor device comprising:

a refractive index sensor comprising a strip waveguide and a slot waveguide;

a light source for outputting a light signal to the strip waveguide; and

a detector for receiving the light signal from the strip waveguide for analysis with respect to the analyte;

wherein the strip waveguide is configured to receive the light signal therein from the light source and transmit the light signal, subject to manipulation as it propagates through the strip waveguide, to the detector for analysis, the slot waveguide is configured for sensing the analyte disposed thereon and for receiving a sensing signal, corresponding to said manipulation of the light signal, from the strip waveguide,

a grating is formed on a surface of the strip waveguide to enable coupling of the sensing signal from the strip waveguide to the slot waveguide, and

the refractive index sensor is configured with enhanced sensitivity based on a sensitivity difference between the slot waveguide and the strip waveguide, and/or a group index difference between the slot waveguide and the strip waveguide.

Preferably, the refractive index sensor device further comprises a polarization controller for receiving the light signal from the light source, and outputting a TE polarized light signal to the strip waveguide.

## BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

FIG. 1A depicts a schematic perspective view of the RI sensor according to an exemplary embodiment of the present invention;

FIG. 1B depicts a schematic cross-sectional view of the RI sensor;

FIG. 2 illustrates the coupling of the sensing signal from the strip waveguide to the slot waveguide and shows the transmission spectra at the outputs of the two waveguides;

FIGS. 3A and 3B depict the field distributions for the strip waveguide and slot waveguide, respectively, of the sensor having exemplary parameters.

FIG. 3C depicts a graph showing the dependences of the mode index  $N_{eff}$  of the two waveguides and the mode index difference  $\Delta N_{eff}$  between the two waveguides **104**, **112** as a function of the wavelength **2**;

FIG. 3D depicts a graph showing the dependences of the mode index  $N_{eff}$  of the two waveguides and the mode index difference  $\Delta N_{eff}$  between the two waveguides **104**, **112** as a function of the external refractive index  $n_{ex}$ ;

FIG. 4 depicts a schematic cross-sectional view of a sensor according to another embodiment of the present invention whereby the strip waveguide is isolated.

FIGS. 5A to 5C show the sensitivity of the two sensors (i.e., with and without isolation) against the width  $W_s$  of the slot waveguide, the width  $g$  of the gap **124** of the slot waveguide, and the rib height  $t$ ;

FIG. 6 depicts the variation of the coupling coefficient and corresponding grating lengths required for achieving  $\kappa L = \pi/2$  as a function of the etch depth for three exemplary values of separation distance  $s$ ;

FIGS. 7A and 7B show the transmission spectra for the two sensors (i.e., without and with isolation), respectively, at different values of external refractive index  $n_{ex}$ ;

FIG. 7C illustrates the linear dependence of the resonance wavelength  $\lambda_0$  on the external refractive index  $n_{ex}$ ;

FIG. 8A depicts a schematic cross-sectional view of a sensor according to yet another embodiment of the present invention for reducing temperature dependence of the sensor.

FIG. 8B shows the temperature dependence of the resonance wavelength for the sensors of FIGS. 1B, 4 and 8 at different values of strip waveguide width;

FIG. 9 depicts a sensor according to an embodiment of the present invention configured for enabling wavelength multiplexed measurement;

FIG. 10 depicts a refractive index sensor device for analysing an analyte according to an embodiment of the present invention; and

FIG. 11 depicts a flow chart generally illustrating a method of fabricating a refractive index sensor for analysing an analyte according to an embodiment of the present invention.

## DETAILED DESCRIPTION

Embodiments of the present invention seek to provide a highly sensitive reflective index (RI) sensor for analyzing an analyte, and a method of fabricating the reflective index sensor. Details of the RI sensor according to exemplary embodiments of the present invention will now be described.

FIG. 1A depicts a schematic perspective view and FIG. 1B depicts a schematic cross-sectional view of the RI sensor **100** according to an exemplary embodiment of the present inven-

tion. As illustrated, the sensor **100** for analysing an analyte, such as in biochemical analysis, includes a strip waveguide **104** for receiving an input light signal therein and transmitting the light signal, subject to manipulation as it propagates through the strip waveguide **104**, to a detector for analysis with respect to the analyte **108**. For example, the input light signal may be a broad-band light from a broad-band optical light source **1004** and the detector may be an optical spectrum analyser (OSA) **1008** as shown in FIG. **10**. The input light signal is received at one end (e.g., an input end) **105** from the light source **1004** and output at another end (e.g., an output end) **106** of the strip waveguide **104**. The sensor **100** further includes a slot waveguide **112** for sensing the analyte **108** disposed thereon and for receiving a sensing signal, corresponding to the above-mentioned manipulation of the light signal, from the strip waveguide **104**. With this configuration, the slot waveguide **112** functions as a sensing waveguide while the strip waveguide **104** functions as a signal waveguide for the optical signal.

In practice, the analyte **108** may be disposed in a sensing area **113** generally indicated by the dashed enclosure in FIG. **1A**, and preferably on a section **115** of the slot waveguide **112** opposing a grating section **116** (described below) of the strip waveguide **104**. In the exemplary embodiment of FIGS. **1A** and **1B**, the analyte **108** is shown in FIG. **1B** to be disposed on or covers both the strip waveguide **104** and the slot waveguide **112** in the sensing area **113**. However, it is neither necessary nor essential for the analyte to be disposed on the strip waveguide **104** since it is the slot waveguide **112** that functions as the sensing waveguide.

The sensor **100** preferably further includes a substrate **114**, and the strip waveguide **104** and the slot waveguide **112** are disposed on the substrate **114** so as to be side by side. More specifically, the strip waveguide **104** and the slot waveguide **112** are spaced apart by a distance *s* (see FIG. **1B**) and substantially parallel to each other.

In the exemplary embodiment, a grating **116** is formed on a surface **118** of the strip waveguide **104** to enable coupling of the sensing signal from the strip waveguide **104** to the slot waveguide **112**. This coupling of the sensing signal is schematically illustrated in FIG. **2**. The sensing signal is in the form of a light signal, and the grating **116** has a grating period  $\Lambda$  configured to couple light signal at a particular resonant wavelength  $\lambda_0$  from the strip waveguide **104** to the slot waveguide **112**. Furthermore, the sensor **100** is configured with enhanced sensitivity based on a sensitivity difference  $\Delta S$  between the slot waveguide **112** and the strip waveguide **104**, and/or a group index difference  $\Delta N_g$  between the slot waveguide **112** and the strip waveguide **104**. This will be described in further detail later below.

The slot waveguide **112** comprises two parallel strips (or rails) **122** having a high refractive index separated by a low-index region (i.e., slot or gap) **124**. As shown in FIG. **1B**, the strip waveguide **104** has a width *W*, the slot waveguide **112** has a width *W<sub>s</sub>*, and the gap **124** has a width *g*. The strip waveguide **104** and the slot waveguide **112** may have the same height *h* and rib height *t*. For clarity and illustration purpose, exemplary embodiments are hereinafter described with the strip waveguide **104** and slot waveguide **112** made of silicon nitride ( $\text{Si}_3\text{N}_4$ ), and the substrate **114** made of  $\text{SiO}_2$ . It will be appreciated to a person skilled in the art that the waveguides **104**, **112** and the substrate **114** are not limited to such materials and other suitable/appropriate materials are within the scope of the present invention. For example, the strip waveguide **104** and the slot waveguide **112** may instead

skilled in the art that the above-mentioned design parameters of the sensor (e.g., *g*, *W*, *W<sub>s</sub>*, *s*, etc.) **100** may also have to be adjusted accordingly. In FIG. **1B**, the refractive index of  $\text{Si}_3\text{N}_4$ ,  $\text{SiO}_2$ , and the external medium (analyte) **108** are denoted as  $n_{\text{Si}_3\text{N}_4}$ ,  $n_{\text{SiO}_2}$  and  $n_{\text{ex}}$ , respectively.

As shown in FIG. **1A**, the grating **116** is formed on a top surface **118** of the strip waveguide **104**. Without the grating **116**, no light coupling would occur between the strip waveguide **104** and the slot waveguide **112** since they are not synchronous in phase (i.e. they have different propagation constants). In the exemplary embodiment, the phase synchronism is achieved with the grating **116** formed on the top surface **118** of the strip waveguide **104**. In this regard, with a predetermined grating period  $\Lambda$ , a light power transfer from the strip waveguide **104** to the slot waveguide **112** is obtained at a particular wavelength (resonance wavelength  $\lambda_0$ ) satisfying the phase-matching condition:

$$\lambda_0 = (N_{\text{eff}}^{\text{strip}} - N_{\text{eff}}^{\text{slot}}) \Lambda = \Delta N_{\text{eff}} \Lambda, \quad (1)$$

where  $N_{\text{eff}}^{\text{strip}}$  and  $N_{\text{eff}}^{\text{slot}}$  are the mode indices of the strip waveguide **104** and slot waveguide **112**, respectively. Therefore, according to Equation (1), the grating coupler **116** is wavelength-selective. As illustrated in FIG. **2**, when a broad-band light **204** is launched into the strip waveguide **104**, light at the resonance wavelength  $\lambda_0$  is coupled to the slot waveguide **112**. This produces a band-rejection spectrum **208** (center wavelength at  $\lambda_0$ ) in the launching strip waveguide **104** while a band-pass spectrum **212** (center wavelength at  $\lambda_0$ ) in the neighbouring slot waveguide **112**. FIG. **2** shows the transmission spectra **208**, **212** at the outputs of the two waveguides **104**, **112** as a result of the grating coupler **116** having a predetermined grating period  $\Lambda$ . This illustrates the manipulation of the input light signal **204** as it propagates through the strip waveguide **104**, and the sensing signal coupled to the slot waveguide **112** corresponding to such a manipulation of the input light signal **204**.

As shown in FIGS. **1A** and **1B**, the slot waveguide **112** functions as a sensing waveguide while the strip waveguide **104** functions as a signal waveguide for the optical signal guiding and detection. As the refractive index of the analyte ( $n_{\text{ex}}$ ) **108** changes, the mode indices of the slot waveguide **112** and strip waveguide **104** change accordingly. This therefore results in a change in the difference  $\Delta N_{\text{eff}}$  between the mode indices of the strip waveguide **104** ( $N_{\text{eff}}^{\text{strip}}$ ) and the slot waveguide **112** ( $N_{\text{eff}}^{\text{slot}}$ ), which in turn leads to a shift in the resonance wavelength  $\lambda_0$  of the light coupled from the strip waveguide **104** to the slot waveguide **112**. The resonance wavelength  $\lambda_0$  of the light signal **206** output from the strip waveguide **104** will therefore shift correspondingly and can be detected by the detector **1008**. Accordingly, the analyte **108** may be analysed based on this shift in the resonant wavelength  $\lambda_0$ . Accordingly, the sensitivity *S* of the sensor **100** may be defined as the degree of such a shift in the resonant wavelength  $\lambda_0$  in response to the analyte **108**.

With the configuration of the sensor **100** as described in the example embodiment, the RI sensitivity *S* of the sensor **100** may be defined as:

$$S = \frac{d\lambda_0}{dn_{\text{ex}}} = \frac{\lambda_0}{(N_g^{\text{strip}} - N_g^{\text{slot}})} \left( \frac{\partial N_{\text{eff}}^{\text{strip}}}{\partial n_{\text{ex}}} - \frac{\partial N_{\text{eff}}^{\text{slot}}}{\partial n_{\text{ex}}} \right) = \lambda_0 \frac{\Delta S}{\Delta N_g} \quad (2)$$

where



-continued

$$N_g^{strip} = N_{eff}^{strip} - \lambda \frac{dN_{eff}^{strip}}{d\lambda}, \quad (3)$$

$$N_g^{slot} = N_{eff}^{slot} - \lambda \frac{dN_{eff}^{slot}}{d\lambda},$$

$$\Delta N_g = N_g^{strip} - N_g^{slot},$$

$$S^{strip} = \frac{\partial N_{eff}^{strip}}{\partial n_{ex}}, \quad (4)$$

$$S^{slot} = \frac{\partial N_{eff}^{slot}}{\partial n_{ex}},$$

$$\Delta S = S^{strip} - S^{slot}.$$

According to Equations (2) to (4), it is found that the sensitivity  $S$  of the sensor **100** described in the example embodiment is proportional to the sensitivity difference  $\Delta S$  between the strip waveguide **104** and the slot waveguide **112**. With this configuration, due to the high intensity field distribution in the slot region **124** of the slot waveguide **112**, the sensitivity  $S^{slot}$  of the slot waveguide **112** is much larger than that  $S^{strip}$  of the strip waveguide **104**, therefore resulting in a larger sensitivity difference  $\Delta S$ . In addition, as can be seen from Equation (2), the sensitivity  $S$  of the sensor **100** is also inversely proportional to the group index difference  $\Delta N_g$  between the strip waveguide **104** and the slot waveguide **112**. The group index difference  $\Delta N_g$  according to the example embodiment is configured to have a small value. Accordingly, the sensor **100** can be configured with greatly enhanced sensitivity based on the above factors (i.e., the sensitivity difference  $\Delta S$  and/or the group index difference  $\Delta N_g$ ). In contrast, the sensitivity of conventional single slot or strip waveguide based sensors is typically only inversely proportional to the group index  $N_g$  (i.e., not the group index difference) which generally has a much larger value (e.g., about 2 to 4). Therefore, such conventional sensors have a much smaller sensitivity.

For illustrate purpose only and without limitation, a sensor **100** according to the exemplary embodiment having the following exemplary parameters will now be examined, including an exemplary calculation of the sensitivity  $S$  of the sensor **100**. In particular, the exemplary parameters are:  $n_{Si3N4}=2.0$ ,  $n_{ex}=1.333$ ,  $n_{SiO2}=1.444$ ,  $h=400$  nm,  $g=200$  nm,  $s=1$   $\mu$ m,  $W=1$   $\mu$ m,  $W_s=450$  nm, and  $t=0$  nm. In this example, only the TE polarization is considered.

FIGS. 3A and 3B show the field distributions for the strip waveguide **104** and slot waveguide **112**, respectively, of the sensor **100** with the above-mentioned exemplary parameters. It can be observed from FIG. 3B that the light intensity inside the nanoscale (200 nm) low refractive index slot region **124** of the slot waveguide **112** is very strong. FIGS. 3C and 3D illustrate the graphs showing the dependences of the mode index  $N_{eff}$  of the two waveguides **104**, **112** and the mode index difference  $\Delta N_{eff}$  between the two waveguides **104**, **112** as a function of the wavelength  $\lambda$  (i.e., FIG. 3C) and external refractive index  $n_{ex}$  (i.e., FIG. 3D). Therefore, the group index  $N_g^{strip}$ ,  $N_g^{slot}$  and the sensitivity  $S^{strip}$ ,  $S^{slot}$  of each waveguide **104**, **112** may be calculated from the graphs shown in FIGS. 3C and 3D. The characteristics/properties of the sensor **100** calculated, including the sensitivity  $S$  of the sensor **100**, are shown in Table 1 below.

TABLE 1

| Properties of the exemplary sensor shown in FIG. 1A (having the above-mentioned exemplary parameters) |              |              |             |            |            |   |
|---|--------------|--------------|-------------|------------|------------|---|
| $N_g^{strip}$   | $N_g^{slot}$ | $\Delta N_g$ | $S^{strip}$ | $S^{slot}$ | $\Delta S$ | Sensitivity (S)<br>$d\lambda_0/dn_{ex}$<br>(nm/RIU) |
| 2.0479  | 1.7902       | 0.2577       | 0.1793      | 0.4222     | -0.2429    | -1461.0   |

As shown in Table 1, the sensitivity  $S$  of the sensor **100** in this example can advantageously be as large as -1461 nm/RIU. It will be understood that the negative sign implies that the resonance wavelength  $\lambda_0$  decreases as the external refractive index increases ( $n_{ex}$ ). Significantly, this sensitivity  $S$  value is about 20 times larger than that of a conventional strip waveguide ring resonator sensor and about 7 times larger than a conventional slot waveguide ring resonator sensor.

Therefore, the configuration of the sensor **100** as described in the exemplary embodiment (i.e., based on the sensitivity difference  $\Delta S$  between the slot waveguide and the strip waveguide, and/or the group index difference  $\Delta N_g$  between the slot waveguide **112** and the strip waveguide **104**) has been demonstrated to advantageously result in a highly sensitive refractive index sensor **100**.

According to further embodiments of the present invention, the sensitivity ( $S$ ) of the sensor **100** can be further enhanced by configuring/adjusting the sensitivity difference  $\Delta S$  between the slot waveguide **112** and the strip waveguide **104**, and/or the group index difference  $\Delta N_g$  between the slot waveguide **112** and the strip waveguide **104**. This is evident from Equation (2) described above which shows that

$$S = \lambda_0 \frac{\Delta S}{\Delta N_g}.$$

Therefore, by configuring the sensor **100** such that the sensitivity difference  $\Delta S$  between the slot waveguide **112** and the strip waveguide **104** is increased and/or the group index difference  $\Delta N_g$  between the slot waveguide **112** and the strip waveguide **104** is reduced, the sensitivity  $S$  of the sensor **100** may be further enhanced.

In exemplary embodiments, to increase the sensitivity difference  $\Delta S$  between the slot waveguide **112** and the strip waveguide **104**, the sensitivity  $S^{strip}$  of the strip waveguide **104** is decreased and/or the sensitivity  $S^{slot}$  of the slot waveguide **112** is increased. In a preferred embodiment, the sensitivity  $S^{strip}$  of the strip waveguide **104** is decreased by isolating the strip waveguide **104** as illustrated in FIG. 4. The sensor **400** depicted in FIG. 4 is the same as the sensor **100** depicted in FIG. 1B, except that the strip waveguide **104** of the sensor **400** is enclosed by an insulation layer **404** to isolate it from the external analyte **108**. It should be noted that the same or similar reference numerals in FIGS. 1A and 1B are applied to the same or similar parts/components throughout the drawings (including FIG. 4), and the description of the same or similar parts/components will be omitted or simplified. A preferred or suitable material for the isolation layer **404** is silicon dioxide ( $SiO_2$ ). It will be appreciated to a person skilled in the art that the isolation layer **404** is not limited to an  $SiO_2$  isolation layer and other suitable/appropriate materials are within the scope of the present invention. For example, in a preferred embodiment described with reference to FIG. 8A later below, the isolation layer is made of a low index material

such as a polymer material (e.g., an epoxy resin such as SU-8 and various types of photoresist).

For illustrate purpose only and without limitation, the characteristics/properties of the sensor **400** having the same exemplary parameters as described hereinbefore and with the SiO<sub>2</sub> isolation layer depicted in FIG. 4 are calculated and shown in Table 2 below.

TABLE 2

| Properties of the exemplary sensor shown in FIG. 4 (having the above-mentioned exemplary parameters). |              |              |             |            |            |   |
|---|--------------|--------------|-------------|------------|------------|---|
| $N_g^{strip}$   | $N_g^{slot}$ | $\Delta N_g$ | $S_{strip}$ | $S_{slot}$ | $\Delta S$ | Sensitivity (S)<br>$d\lambda_0/dn_{ex}$<br>(nm/RIU) |
| 2.0248  | 1.7858       | 0.2390       | 0.0026      | 0.4193     | -0.4167    | -2702.4   |

By comparing the sensitivity  $S_{strip}$  of the strip waveguide **104** in Tables 1 and 2, it can be clearly seen that  $S_{strip}$  is significantly reduced after the SiO<sub>2</sub> isolation. As a result, the sensitivity difference  $\Delta S$  between the slot waveguide **112** and the strip waveguide **104** increased significantly, which therefore leads to a correspondingly large increase in the sensitivity of the sensor **400**. As shown in Table 2, the sensitivity of the sensor **400** calculated is about -2702.4 nm/RIU which is almost 2 times larger than that the sensor **100** described hereinbefore without the strip waveguide being isolated. This demonstrates an effective way to decrease the sensitivity of the strip waveguide **104** in the interest of increasing the sensitivity of the sensor **400**.

As mentioned above, the sensitivity difference  $\Delta S$  between the slot waveguide **112** and the strip waveguide **104** can also be increased by increasing the sensitivity  $S_{slot}$  of the slot waveguide **112**. In an embodiment, this can be achieved by configuring one or more parameters of the slot waveguide **112**. To demonstrate this, FIGS. 5A, 5B, and 5C show the sensitivity S of the sensors **100**, **400** against the width  $W_s$  (in the range of about 350 nm to 550 nm) of the slot waveguide **112**, the width  $g$  (in the range of about 100 nm to 300 nm) of the gap **124** of the slot waveguide **112**, and the rib height  $t$  (in the range of 0 to 100 nm). From FIGS. 5A and 5B, for both sensors **100**, **400**, it can be clearly seen that the sensitivity S increases as the width  $W_s$  of the slot waveguide **112** and/or the width  $g$  of the gap **124** of the slot waveguide **112** decreases. Therefore, it has been demonstrated that by configuring/adjusting the parameters of the slot waveguide **112**, the sensitivity S of the sensors **100**, **400** can be as high as about 1700 nm/RIU and 3500 nm/RIU, respectively. On the other hand, from FIG. 5C, the sensitivity S of the sensors **100**, **400** has only be found to weakly depend on the rib height  $t$ .

In a preferred embodiment, the width  $W_s$  of the slot waveguide **112** is in the range of about 350 nm to 550 nm, and more preferably 450 nm to 550 nm, the width  $g$  of the gap **124** of the slot waveguide **112** is in the range of about 100 nm to 300 nm, and more preferably 100 nm to 200 nm, and the rib height  $t$  is in the range of about 0 nm to 100 nm.

The coupling coefficient and the transmission spectrum of the grating **116** will now be described. The transmission spectrum at the output of the strip waveguide **104** can be obtained based on the following equation:

$$T(\lambda) = 1 - \frac{\kappa^2}{\kappa^2 + \delta^2/4} \sin^2 \sqrt{\kappa^2 + \delta^2/4} L \quad (5)$$

where

$$\delta = \frac{2\pi}{\lambda} \Delta N_{eff} - \frac{2\pi}{\Lambda} \quad (6)$$

In the above equations, L is the grating length and  $\kappa$  is the coupling coefficient used to characterize the strength of the grating and is obtained with:

$$\kappa = \frac{2(n_{Si_3N_4}^2 - n_{ex}^2)}{\lambda c \mu_0} \int_A \vec{e}_{strip} \cdot \vec{e}_{slot}^* dA, \quad (7)$$

where c and  $\mu_0$  are the speed of light in free space and the vacuum permeability.  $\vec{e}_{strip}$  and  $\vec{e}_{slot}$  are the normalized fields of strip waveguide **104** and slot waveguide **112**, respectively. A denotes the grating area. According to Equation (5), when  $\kappa L = \pi/2$  and  $\delta = 0$ , 100% coupling occurs at the resonance wavelength  $\lambda_0$ .

According to an embodiment, the grating strength (i.e., coupling coefficient) can be controlled by configuring the grating etch depth on the top surface **118** of the strip waveguide **104**. To demonstrate this, FIG. 6 shows the variation of the coupling coefficient as a function of the etch depth for three values of separation distance s. It can be observed that the coupling coefficient increases as the etch depth increases. In addition, smaller separation distance results in larger coupling coefficient at the same etch depth. The corresponding grating lengths required for achieving  $\kappa L = \pi/2$  are also shown in FIG. 6. For example, with  $L = 1500 \mu m$ , the coupling coefficient required for achieving a maximum contrast is given by  $\kappa = \pi/2 L = 1.047 \times 10^3 m^{-1}$ , which according to FIG. 6, requires an etch depth of about 28 nm (about 7% of the thickness of the waveguide height).

FIGS. 7A and 7B show the transmission spectra for the two sensors **100**, **400** (i.e., without and with SiO<sub>2</sub> isolation), respectively, at different values of external refractive index  $n_{ex}$ . The grating lengths for both sensors **100**, **400** are set to 2000  $\mu m$ . In both Figures, the resonance wavelength  $\lambda_0$  shifted to shorter wavelength as the external refractive index increases. By comparing FIGS. 7A and 7B, it can be observed that the sensor **400** with SiO<sub>2</sub> isolation is more sensitive than the sensor **100** without SiO<sub>2</sub> isolation. In FIG. 7C, the dependence of the resonance wavelength  $\lambda_0$  on the external refractive index  $n_{ex}$  are shown to be linear.

In a further embodiment, a sensor **800** as depicted in FIG. 8A is configured with reduced or minimal temperature dependence. The sensor **800** depicted in FIG. 8A is the same as the sensor **100** depicted in FIG. 1B or the sensor **400** depicted in FIG. 4 except that the strip waveguide **104** of the sensor **400** is isolated or enclosed by a polymer layer **804**. It should be noted that the same or similar reference numerals are applied to the same or similar parts/components throughout the drawings, and the description of the same or similar parts/components will be omitted or simplified.

In the embodiment, the temperature dependence of the resonance wavelength  $\lambda_0$  is calculated as follow:

$$\frac{d\lambda_0}{dT} = \frac{\lambda_0}{\Delta N_g} \left( \frac{\partial \Delta N_{eff}}{\partial n_{SiO_2}} C_{SiO_2} + \frac{\partial \Delta N_{eff}}{\partial n_{ex}} C_{ex} + \right) \quad (8)$$

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$$\begin{aligned} & \text{-continued} \\ & \left( \frac{\partial \Delta N_{\text{eff}}}{\partial n_{\text{cover}}} C_{\text{cover}} + \frac{\partial \Delta N_{\text{eff}}}{\partial n_{\text{Si}_3\text{N}_4}} C_{\text{Si}_3\text{N}_4} \right) = \frac{\lambda_0}{\Delta N_g} F_t, \end{aligned}$$

where  $C_{\text{SiO}_2}$ ,  $C_{\text{ex}}$ ,  $C_{\text{cover}}$ ,  $C_{\text{Si}_3\text{N}_4}$  are thermal-optic coefficients (TOC) for the  $\text{SiO}_2$  substrate **114**, external analyte **108**, polymer cover layer **804** for isolation, and  $\text{Si}_3\text{N}_4$ , respectively. In this example, it was found that the sensor **400** has a positive temperature dependence (i.e., resonance wavelength  $\lambda_0$  shifts to longer wavelength as temperature increases). To address this positive temperature dependence, the embodiment provides a polymer cover **804** with a negative TOC as an isolation layer instead of the  $\text{SiO}_2$  layer **404** as disclosed in the embodiment of FIG. **4** to compensate for the temperature dependence of the sensor **400**. It was found that  $F_t$  in Eq. (8) can be a small value close to zero when a polymer material with an appropriate negative TOC is used. That is, selecting a polymer material having a TOC which can substantially compensate the positive temperature dependence of the sensor such that the net temperature dependence is minimal or substantially reduced, and vice versa. Therefore, the temperature dependence of the sensor **800** can advantageously be significantly reduced or substantially eliminated.

For illustration purpose, an experiment was conducted for each of the sensors **100**, **400**, **800** with the following parameters:  $C_{\text{SiO}_2} = 1.0 \times 10^{-5}/^\circ\text{C}$ .,  $C_{\text{ex}} = -8.0 \times 10^{-5}/^\circ\text{C}$  (i.e., for water),  $C_{\text{cover}} = -1.8 \times 10^{-4}/^\circ\text{C}$ .,  $C_{\text{Si}_3\text{N}_4} = 4.0 \times 10^{-5}/^\circ\text{C}$ .,  $n_{\text{cover}} = 1.49$  (the TOC and the refractive index are typical values of polymers). FIG. **8B** shows the temperature dependence of the resonance wavelength for each of the three sensors **100**, **400**, **800** at different values of strip waveguide width (from 900 nm to 1000 nm). It can be seen that the sensors without and with  $\text{SiO}_2$  isolation (i.e., **100**, **400**) have a positive temperature dependence of about 200 pm/ $^\circ\text{C}$  and about 310 pm/ $^\circ\text{C}$ ., respectively. On the other hand, when a polymer isolation layer **804** is used, the temperature dependence is significantly reduced to be less than 20 pm/ $^\circ\text{C}$  for a large range of strip waveguide width (i.e., large tolerance). In addition, the temperature dependence can be further reduced to substantially zero by choosing a strip waveguide **104** having a width of about 950 nm. This can be derived from FIG. **8B** since the crossing point of the dashed line (corresponding to zero temperature sensitivity) and the curve with polymer isolation is located when  $W$  is around 950 nm. Therefore by applying a polymer isolation layer **804**, not only is the sensitivity enhanced, but the temperature dependence is also greatly reduced. In general, any polymer material that has an appropriate TOC is suitable, and preferably the polymer material is patternable. For example and without limitation, the polymer material may be WIR30-490 or SU-8.

According to another embodiment, the sensor **900** is configured so as to enable wavelength multiplexed measurement. As mentioned hereinbefore, the grating **116** is intrinsically wavelength-selective. Therefore, the sensor **100**, **400**, **800** can be extended to a configuration suitable for wavelength multiplexed measurement. FIG. **9** illustrates a top schematic view of a sensor **900** capable of wavelength multiplexed sensing where four cascaded gratings **116a**, **116b**, **116c**, and **116d** with different periods  $\Lambda_1$ ,  $\Lambda_2$ ,  $\Lambda_3$ , and  $\Lambda_4$  (corresponding to different resonance wavelengths) are formed along the top surface **118** of the strip waveguide **104**. Each grating **116** generates a sensing signal at the respective resonance wavelength  $\lambda_1$ ,  $\lambda_2$ ,  $\lambda_3$ , and  $\lambda_4$ , therefore, a spectrum with four peaks can be observed at the output of the strip waveguide **104**. The wavelength of each peak can then be monitored or detected for wavelength multiplexed measurement.

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Accordingly, embodiments of the present invention provide a highly sensitive refractive index sensor, such as in biochemical analysis, based on grating assisted co-directional light coupling between a strip waveguide **104** and a slot waveguide **112**. The sensor has a high sensitivity and can be further enhanced by isolating the strip waveguide **104** and/or optimizing the slot waveguide parameters. With a polymer isolation layer, the sensor can further achieve minimal or significantly reduced temperature dependence. In addition, the sensor can be configured to have wavelength multiplexed measurement capability due to the intrinsic wavelength-selective property of the gratings. The sensors disclosed in the exemplary embodiments have a wide range of applications such as but not limited to clinical applications where multiplexed detection of biomolecules with low detection limit is desirable. For example, other applications can be in the fields of environmental monitoring, and food safety and drug screening, such as a gas sensor for low-concentration explosive gas detection.

FIG. **10** depicts a refractive index sensor device **1000** for analysing an analyte incorporating the refractive index sensor **100**, **400** or **800** described hereinbefore according to exemplary embodiments of the present invention. In particular, the refractive index sensor device **1000** includes a refractive index sensor **100**, **400**, or **800** comprising a strip waveguide **104** and a slot waveguide **112**, a light source (e.g., a broadband optical source) **1004** for outputting a light signal to the strip waveguide **104**, and a detector (e.g., an optical spectrum analyzer (OSA)) **1008** for receiving the light signal from the strip waveguide **104** for analysis (preferably wavelength shift analysis) with respect to the analyte **108**. The strip waveguide **104** is configured to receive the light signal therein from the light source **1004** and transmit the light signal, subject to manipulation as it propagates through the strip waveguide, to the detector **1008** for analysis. The slot waveguide **112** is configured for sensing the analyte disposed thereon and for receiving a sensing signal, corresponding to the above-mentioned manipulation of the light signal, from the strip waveguide **104**. Furthermore, a grating **116** is formed on a surface of the strip waveguide **104** to enable coupling of the sensing signal from the strip waveguide **104** to the slot waveguide **112**. In particular, the refractive index sensor **100**, **400**, or **800** is configured with enhanced sensitivity based on a sensitivity difference between the slot waveguide **112** and the strip waveguide **104**, and/or a group index difference between the slot waveguide **112** and the strip waveguide **104**.

Preferably, the refractive index sensor device **1000** further includes a polarization controller **1006** for receiving the light signal from the light source **1004**, and outputting a TE polarized light signal to the strip waveguide.

FIG. **11** depicts a flow chart generally illustrating a method **1100** of fabricating a refractive index sensor for analysing an analyte. The method **1100** includes a step **1102** of forming a strip waveguide for receiving an input light signal therein and transmitting the light signal, subject to manipulation as it propagates through the strip waveguide **104**, to a detector (e.g., an optical spectrum analyzer) **1008** for analysis with respect to the analyte **108**, and a step **1104** of forming a slot waveguide **112** for sensing the analyte **108** disposed thereon and for receiving a sensing signal, corresponding to the above-mentioned manipulation of the light signal, from the strip waveguide **104**. The method **1100** further includes a step **1106** of forming a grating on a surface of the strip waveguide to enable coupling of the sensing signal from the strip waveguide to the slot waveguide. It will be appreciated to a person skilled in the art that the above-described steps may be performed in any order and are not limited to the order pre-

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sented. Furthermore, the above steps are not intended to be construed to necessitate individual steps and may be combined as one fabrication step where appropriate without deviating from the scope of the present invention.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

The invention claimed is:

1. A refractive index sensor for analysing an analyte, the sensor comprising:

a strip waveguide for receiving an input light signal therein and transmitting the light signal, subject to manipulation as it propagates through the strip waveguide, to a detector for analysis with respect to the analyte; and

a slot waveguide for sensing the analyte disposed thereon and for receiving a sensing signal, corresponding to said manipulation of the light signal, from the strip waveguide,

wherein a grating is formed on a surface of the strip waveguide to enable coupling of the sensing signal from the strip waveguide to the slot waveguide, and

the sensor is configured with enhanced sensitivity based on a sensitivity difference between the slot waveguide and the strip waveguide, and/or a group index difference between the slot waveguide and the strip waveguide.

2. The sensor according to claim 1, further comprises a substrate, wherein the strip waveguide and the slot waveguide are disposed on the substrate so as to be spaced apart and substantially parallel to each other.

3. The sensor according to claim 1, wherein the sensing signal is in the form of a light signal, and the grating has a grating period configured to couple light signal at a particular resonant wavelength from the strip waveguide to the slot waveguide.

4. The sensor according to claim 3, wherein the slot waveguide has a mode index which is subject to change based on the analyte disposed thereon, the change in the mode index results in a shift in the particular resonant wavelength of the light signal coupled from the strip waveguide to the slot waveguide, thereby enabling analysis of the analyte based on the shift in the particular resonant wavelength.

5. The sensor according to claim 3, wherein the sensor is configured such that its sensitivity (S) is determined based on the following equation:

$$S = \lambda_0 \frac{\Delta S}{\Delta N_g}$$

where,  $\lambda_0$  is the particular resonant wavelength of the light signal,  $\Delta S$  is the sensitivity difference between the slot waveguide and the strip waveguide, and  $\Delta N_g$  is the group index difference between the slot waveguide and the strip waveguide.

6. The sensor according to claim 1, wherein the sensor is configured such that the sensitivity difference between the slot waveguide and the strip waveguide is increased and/or the group index difference between the slot waveguide and the strip waveguide is reduced.

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7. The sensor according to claim 1, wherein the strip waveguide is isolated to decrease its sensitivity so as to increase the sensitivity difference between the slot waveguide and the strip waveguide.

8. The sensor according to claim 7, wherein the strip waveguide is enclosed by an isolation layer made of SiO<sub>2</sub> to isolate the strip waveguide from the analyte.

9. The sensor according to claim 7, wherein the strip waveguide is enclosed by an isolation layer made of a polymer material to isolate the strip waveguide from the analyte.

10. The sensor according to claim 9, wherein the polymer material has a thermal-optic coefficient selected for compensating a positive or negative temperature dependence of the sensor so as to reduce the temperature dependence of the sensor.

11. The sensor according to claim 10, wherein the polymer material is made of WIR30-490 or SU-8.

12. The sensor according to claim 1, wherein a width of the strip waveguide is configured to be about 600 nm to about 1000 nm.

13. The sensor according to claim 1, wherein one or more parameters of the slot waveguide are configured to increase its sensitivity so as to increase the sensitivity difference between the slot waveguide and the strip waveguide, said one or more parameters include a width of the slot waveguide and/or a width of a gap of the slot waveguide.

14. The sensor according to claim 13, wherein the slot waveguide is configured such that the width of the slot waveguide is increased and/or the width of the gap is reduced.

15. The sensor according to claim 13, wherein the width of the slot waveguide is in the range of about 350 nm to about 550 nm, and the width of the gap is in the range of about 50 nm to about 300 nm.

16. The sensor according to claim 1, wherein a plurality of gratings, spaced apart from each other, is formed on the surface of the strip waveguide, each grating having a different grating period configured for coupling a sensing signal at a respective resonance wavelength to the slot waveguide, thereby enabling wavelength multiplexed measurement.

17. The sensor according to claim 1, wherein the slot waveguide and/or the strip waveguide are made of silicon nitride (Si<sub>3</sub>N<sub>4</sub>).

18. A method of fabricating a refractive index sensor for analysing an analyte, the method comprising:

forming a strip waveguide for receiving an input light signal therein and transmitting the light signal, subject to manipulation as it propagates through the strip waveguide, to a detector for analysis with respect to the analyte; and

forming a slot waveguide for sensing the analyte disposed thereon and for receiving a sensing signal, corresponding to said manipulation of the light signal, from the strip waveguide,

wherein the method further comprises forming a grating on a surface of the strip waveguide to enable coupling of the sensing signal from the strip waveguide to the slot waveguide, and

configuring the sensor with enhanced sensitivity based on a sensitivity difference between the slot waveguide and the strip waveguide, and/or a group index difference between the slot waveguide and the strip waveguide.

19. A refractive index sensor device for analysing an analyte, the sensor device comprising:

a refractive index sensor comprising a strip waveguide and a slot waveguide;

a light source for outputting a light signal to the strip waveguide; and

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a detector for receiving the light signal from the strip waveguide for analysis with respect to the analyte; wherein the strip waveguide is configured to receive the light signal therein from the light source and transmit the light signal, subject to manipulation as it propagates 5 through the strip waveguide, to the detector for analysis, the slot waveguide is configured for sensing the analyte disposed thereon and for receiving a sensing signal, corresponding to said manipulation of the light signal, from the strip waveguide, 10 a grating is formed on a surface of the strip waveguide to enable coupling of the sensing signal from the strip waveguide to the slot waveguide, and the refractive index sensor is configured with enhanced sensitivity based on a sensitivity difference between the slot waveguide and the strip waveguide, and/or a group index difference between the slot waveguide and the strip waveguide. 15

20. The refractive index sensor device according to claim 19, further comprising a polarization controller for receiving 20 the light signal from the light source, and outputting a TE polarized light signal to the strip waveguide.

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